

Guidelines for Left-Turn Lanes

Joseph C. Oppenlander, P.E. (F)* and J. Christopher Bianchi** (ITE Committee 4A-22)

INTRODUCTION

Although special lanes for left-turn movements are provided at both unsignalized and signalized intersections, no standard guidelines are presently available for establishing the need of this geometric feature. Therefore, the assignment for ITE Committee 4A-22, Guidelines for Left-turn Lanes was to develop criteria for the provision of separate left-turn lanes at unsignalized and signalized intersections.

Based on a literature search and on current research efforts, guidelines for left-turn lanes were developed for the following situations.

1. Unsignalized intersection.
 - a. Two-lane roadway.
 - b. Four-lane roadway.
2. Signalized intersection.
 - a. Capacity need.
 - b. Storage requirement.
3. Accident record.

Relevant references for the various sets of guidelines are documented in the appropriate intersectional category. Greater details on the technical aspects are enumerated in the Final Report of Committee 4A-22 (1). Only sample summaries that have been condensed for some situations are presented in this technical paper.

UNSIGNALIZED INTERSECTION

Warranting criteria for left-turn lanes at unsignalized intersections were developed in accordance with the conceptual model proposed by M. D. Harmelink for both two-lane and four-lane roadways (2). This work is based on a queuing model in which arrival and service rates are assumed to follow negative exponential distributions. Arrival rates are determined by the volumes of left-turning and advancing vehicles and by the time required for a left-turning vehicle to clear the advancing lane. For the approach that is being evaluated for a left-turn lane, 'advancing' represents those conditions on this leg of a major roadway at the intersection with a minor roadway that is regulated by stop or yield control. Service rates are functions of the traffic volume that directly opposes the left turn and of the time required for the left-turn maneuver. Selected summary warrants from this study are listed in the publication entitled A Policy on Geometric Design of Highways and Streets, 1984, by the American Association of State Highway and Transportation Officials (3).

Two-lane Roadway

For two-lane roadways, the Harmelink model was extrapolated and solved for design speeds from 30 to 70 mph (corresponding speed limits from 25 to 65 mph and operating speeds from 20 to 60 mph at 5-mph intervals). Sample results are presented in Tables 1 and 2 and in corresponding Figures 1 and 2 for two selected speed categories. The warranting levels of advancing volumes in vehicles per hour are listed in the tables and the figures for various combinations of opposing volumes and percentage of left turns. Wide ranges of these two parameters were selected to cover most design situations. If the actual advancing volume equals or exceeds the tabulated value or is plotted on or above the designated curve, then a left-turn lane is justified to provide an acceptable probability of traffic performance on the approach of the major highway at an unsignalized intersection. The probability levels represent the chances of a left-turning vehicle stopping on the major roadway to wait for an acceptable gap in the opposing traffic and range from 3.00 to 1.00 percent at 0.25-percent intervals for design speeds from 30 to 70 mph at corresponding intervals of 5 mph.

Four-lane Roadway

A similar approach in the Harmelink study was applied to four-lane roadways with probability levels selected as 3.00 and 0.50 percent for undivided and divided facilities, respectively, for all design speeds. The warranting levels of advancing volume in vehicles per hour are noted for various ranges of opposing volumes and percentage of left turns. These guidelines for left-turn lanes are presented in Table 3 and Figure 3 and in Table 4 and Figure 4, respectively, for undivided and divided, four-lane roadways. The application of these tables and figures was previously presented for two-lane roadways.

Details of the Harmelink model are described in the publication entitled "Volume Warrants for Left-Turn Storage Lanes At Unsignalized Grade Intersections" (2) and in the Final Report of ITE Committee 4A-22, Guidelines for Left-turn Warrants (1).

SIGNALIZED INTERSECTION

Two sets of guidelines for left-turn lanes were proposed for roadway approaches at signalized intersections. The first situation involves the necessary capacity for an intersectional approach to operate at an acceptable level of service. The second case relates to the need for storing left-turning vehicles on the approach lanes. Only one condition

* Professor of Civil Engineering
The University of Vermont
Burlington, Vermont

** Civil Engineering Student
The University of Vermont
Burlington, Vermont

needs to be satisfied as a sufficient criterion for providing a left-turn lane on the intersectional approach under evaluation. These two warrants pertain only to the necessity for a left-turn lane and do not relate to the need for a separate left-turn phase.

Capacity Need

The capacity guideline is predicated on the need to provide acceptable levels of service on each approach as well as for the overall operation of the intersection. Applications of the computational methodology for signalized intersections, as outlined in the Highway Capacity Manual, 1985, permit the determination of any needed left-turn lanes to accommodate the demand volumes at a design hour level (4). This technique is most judiciously accomplished with proper capacity software.

An alternate procedure is available for the determination of left-turn capacity on intersectional approaches with two-phase signal operation. The capacity charts are presented in a report entitled "Guidelines for Signalized Left Turn Treatments" and prepared by the Federal Highway Administration (5). The left-turn capacity without a special turn lane can be determined from Figure 5 with one, two, or three lanes of opposing traffic. The left-turn capacity, as read from the appropriate chart, is corrected for trucks and buses by the following equation:

$$Q_{lt} = Q_1 (100 - T)$$

where Q_{lt} = adjusted left-turn capacity, vph; Q_1 = chart left-turn capacity, vph; and T = left-turn trucks and buses, percent.

If adequate left-turn capacity is not available in terms of the left-turn design volume, then a left-turn lane is warranted on that intersectional approach. The adequacy of a single left-turn lane or the need for a double left-turn lane operation can be ascertained from Figure 6 with application of the truck-bus correction. This capacity determination is based on one, two, or three lanes of opposing traffic. Again, a comparison is made between available capacity and demand volume for the left-turning movement to determine the need for two left-turn lanes.

Storage Requirement

In the second case, guidelines for a left-turn lane on an approach at a signalized intersection are based on the requirement for storing at least one left-turning vehicle. This situation was modeled according to queuing theory with a Poisson arrival pattern and an exponential service distribution (6). The arrival rate is based on the design left-turn volume, while the service pattern is a function of the capacity of a left-turn permitted phase and of the traffic volume that opposes this turning movement. The warranting left-turn volume is presented in Table 5 for various arrangements of opposing volumes and green time/cycle length ratios. In addition, the critical left-turn volume is associated with the 50th, 85th, and 95th probability levels for storing at least one left-turning vehicle on an approach at a signalized intersection. A left-turn lane is warranted if the design left-turn volume exceeds the tabulated value for the available green time/cycle length ratio assigned to the approach, the traffic volume that opposes the left-turn movement, and for the desired probability level associated with the need for

vehicular storage on the intersectional approach. As the probability level increases for the storage of a vehicle, the left-turn volume decreases for the warranting case with all other factors held constant.

ACCIDENT RECORD

The safety of the left-turn movement is related to the possibility that left-turning accidents can be reduced by the provision of a special turning lane. An accident guideline for a left-turn lane was developed from research activities that involved accident data collected in Lexington, Kentucky (7). Traffic mishaps related to left-turning movements were based on the following situations:

1. Left-turn vehicle enters the path of an oncoming vehicle;
2. Rear-end collision results with a vehicle waiting to turn left; and
3. A vehicle passes another vehicle that is stopped for a left-turn maneuver.

For critical accident levels that correspond to a probability of 99.5 percent, the following guidelines relate to the provision of a special left-turn lane on an approach:

1. Unsignalized intersection - four accidents per year and
2. Signalized intersection - five accidents per year.

In the application of this guideline, traffic accidents at an intersection are categorized by approach in accordance with the specified collision types that involve left-turning vehicles.

SUMMARY

Guidelines for left-turn lanes at both unsignalized and signalized intersections have been presented in this technical paper. Applications of these criteria to existing locations are essential for validating the feasibility of application in local communities. Complete documentation of all pertinent tables and figures is contained in the Final Report of ITE Committee 4A-22, Guidelines for Left-turn Lanes.

REFERENCES

1. Committee 4A-22, "Final Report on Guidelines for Left-turn Lanes," Institute of Transportation Engineers, July 1990.
2. Harmelink, M.D., "Volume Warrants for Left-Turn Storage Lanes at Unsignalized Grade Intersections," Highway Research Record, No. 211, Highway Research Board, 1967, pp. 1 to 18.
3. American Association of State Highway and Transportation Officials, A Policy on Geometric Design of Highways and Streets, 1984, pp. 822 to 823.
4. Transportation Research Board, Highway Capacity Manual, 1985, pp. 9-1 to 9-84.
5. Federal Highway Administration, "Guidelines for Signalized Left Turn Treatments," FHWA-IP-81-4, November 1981, pp. 22 to 24.
6. Oppenlander, Joseph C., and Jane E. Oppenlander, "Design Lengths for Left-turn Lanes without Separate Signal Phases," 1990, unpublished.
7. Agent, Kenneth R., "Warrants for Left-Turn Lanes," Transportation Quarterly, Eno Foundation, Vol. 37, No. 1, January 1983, pp. 99 to 114.

Table 1
GUIDELINES FOR LEFT-TURN LANE AT UNSIGNALIZED INTERSECTION

Two-lane Roadway Opposing Volume (vph)	Advancing Volume - vph																				Operating Speed = 30 mph Speed Limit = 35 mph Design Speed = 40 mph									
	Left-turn - percent																													
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10	15	20	25	30	35	40	50					
50	2224	1576	1290	1120	1005	920	854	800	757	720	688	660	636	615	596	578	548	523	439	392	362	342	329	320	314					
100	1958	1388	1136	987	885	810	752	705	666	634	606	582	560	541	524	509	483	460	387	345	319	301	290	282	276					
150	1749	1240	1015	881	790	723	671	630	595	566	541	520	501	484	468	455	431	411	346	308	285	269	259	252	247					
200	1598	1133	927	805	722	661	613	575	544	517	494	475	457	442	428	415	394	376	316	282	260	246	236	230	225					
250	1436	1018	833	723	649	594	551	517	489	465	444	426	411	397	385	373	354	338	284	253	234	221	212	207	203					
300	1331	944	773	671	601	550	511	479	453	431	412	395	381	368	357	346	328	313	263	235	217	205	197	192	188					
350	1214	861	704	612	548	502	466	437	413	393	376	361	347	336	325	316	299	285	240	214	198	187	180	175	171					
400	1118	793	649	564	505	462	429	403	381	362	346	332	320	309	300	291	276	263	221	197	182	172	165	161	158					
450	1026	728	596	517	464	424	394	369	349	332	318	305	294	284	275	267	253	241	203	181	167	158	152	148	145					
500	937	664	544	472	423	388	360	337	319	303	290	278	268	259	251	244	231	220	185	165	153	144	139	135	132					
550	869	616	504	438	393	359	334	313	296	281	269	258	249	240	233	226	214	204	172	153	142	134	129	125	123					
600	823	583	477	414	372	340	316	296	280	266	254	244	235	227	220	214	203	193	162	145	134	127	122	118	116					
650	759	538	441	382	343	314	291	273	258	246	235	225	217	210	203	197	187	178	150	134	124	117	112	109	107					
700	717	508	416	361	324	296	275	258	244	232	222	213	205	198	192	186	177	168	142	126	117	110	106	103	101					
750	657	466	381	331	297	272	252	236	223	213	203	195	188	182	176	171	162	154	130	116	107	101	97	95	93					
800	598	424	347	301	270	247	230	215	203	194	185	178	171	165	160	155	147	141	118	105	97	92	88	86	84					
850	560	397	325	282	253	232	215	202	191	181	173	166	160	155	150	146	138	132	111	99	91	86	83	81	79					
900	524	371	304	264	237	217	201	188	178	169	162	156	150	145	140	136	129	123	103	92	85	81	77	75	74					
950	488	346	283	246	221	202	187	176	166	158	151	145	140	135	131	127	120	115	96	86	80	75	72	70	69					
1000	454	322	263	229	205	188	174	163	154	147	140	135	130	125	121	118	112	107	90	80	74	70	67	65	64					
1050	420	298	244	212	190	174	161	151	143	136	130	125	120	116	112	109	103	99	83	74	68	65	62	60	59					
1100	365	258	212	184	165	151	140	131	124	118	113	108	104	101	98	95	90	86	72	64	59	56	54	52	51					
1150	331	235	192	167	150	137	127	119	113	107	102	98	95	92	89	86	82	78	65	58	54	51	49	48	47					
1200	272	193	158	137	123	112	104	98	93	88	84	81	78	75	73	71	67	64	54	48	44	42	40	39	38					
1250	236	168	137	119	107	98	91	85	80	76	73	70	68	65	63	61	58	56	47	42	38	36	35	34	33					
1300	199	141	115	100	90	82	76	72	68	64	62	59	57	55	53	52	49	47	39	35	32	31	29	29	28					

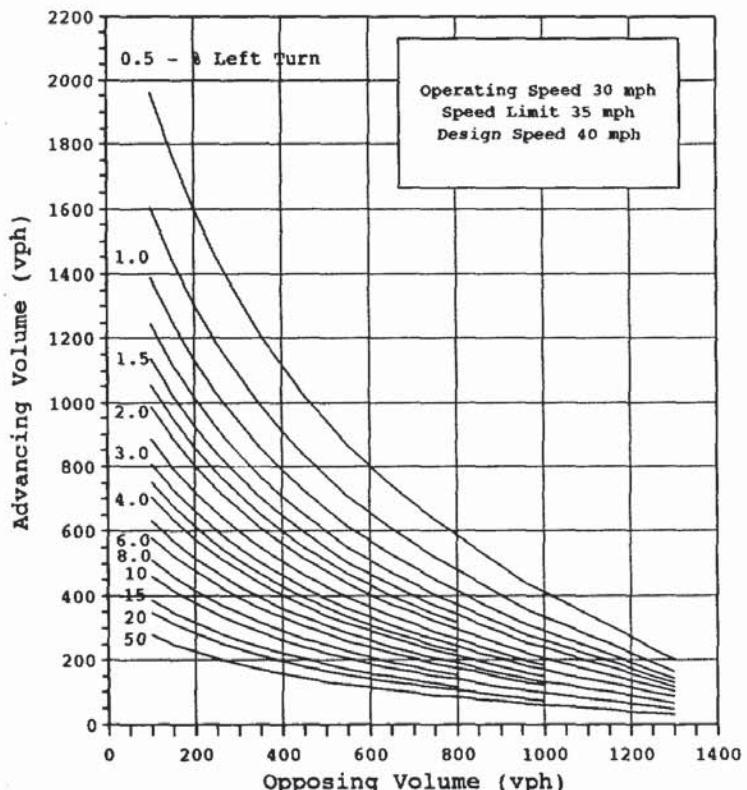


Figure 1 Guidelines for Left-turn Lane at Unsignalized Intersection - Two-lane Roadway

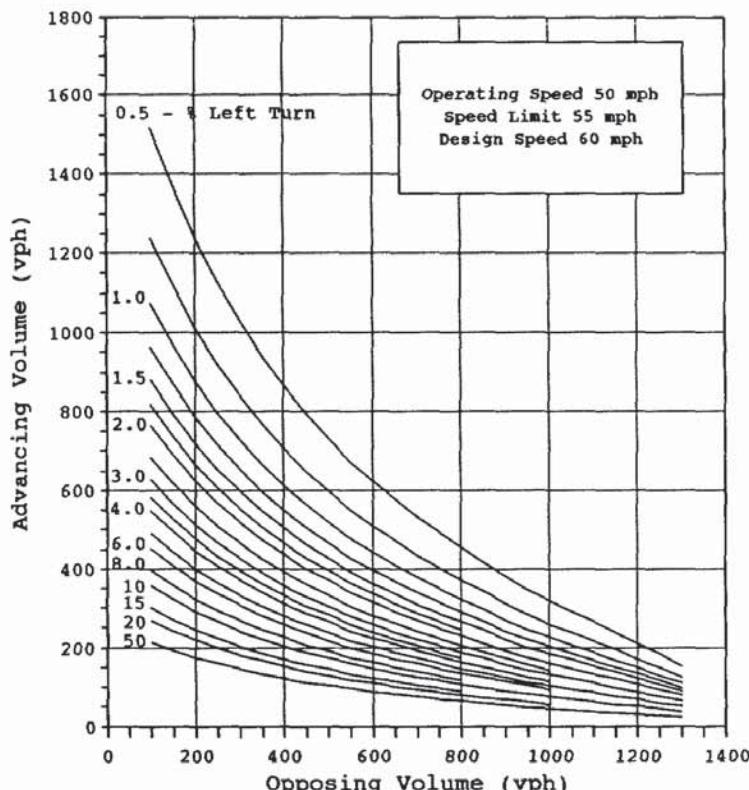


Figure 2 Guidelines for Left-turn Lane at Unsignalized Intersection - Two-lane Roadway

Table 2
GUIDELINES FOR LEFT-TURN LANE AT UNSIGNALIZED INTERSECTION

Two-lane Roadway												Operating Speed = 50 mph													
Opposing Volume (vph)												Speed Limit = 55 mph													
Advancing Volume - vph												Design Speed = 60 mph													
Left-turn - percent																									
0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10	15	20	25	30	35	40	50	
50	1723	1221	1000	868	778	712	661	620	586	557	533	512	493	476	461	448	425	405	340	304	281	265	255	248	243
100	1517	1075	880	764	685	627	582	546	516	491	469	451	434	419	406	394	374	357	300	268	247	233	224	218	214
150	1355	961	786	683	612	560	520	488	461	439	419	402	388	375	363	352	334	319	268	239	221	209	200	195	191
200	1238	878	718	624	559	512	475	446	421	401	383	368	354	342	331	322	305	291	245	218	202	191	183	178	175
250	1112	788	645	560	502	460	427	400	378	360	344	330	318	307	298	289	274	262	220	196	181	171	164	160	157
300	1031	731	598	520	466	426	396	371	351	334	319	306	295	285	276	268	254	242	204	182	168	159	152	148	145
350	940	667	546	474	425	389	361	338	320	304	291	279	269	260	252	244	232	221	186	166	153	145	139	135	133
400	866	614	503	436	391	358	333	312	295	280	268	257	248	240	232	225	214	204	171	153	141	133	128	125	122
450	795	564	461	401	359	329	305	286	271	257	246	236	227	220	213	207	196	187	157	140	130	122	118	114	112
500	726	515	421	366	328	300	279	261	247	235	225	216	208	201	194	189	179	171	143	128	118	112	107	105	102
550	673	477	391	339	304	278	258	242	229	218	208	200	193	186	180	175	166	158	133	119	110	104	100	97	95
600	637	452	370	321	288	263	245	229	217	206	197	189	182	176	171	166	157	150	126	112	104	98	94	92	90
650	588	417	341	296	266	243	226	212	200	190	182	175	168	163	157	153	145	138	116	104	96	91	87	85	83
700	555	394	322	280	251	230	213	200	189	180	172	165	159	153	149	144	137	131	110	98	90	85	82	80	78
750	509	361	295	256	230	210	195	183	173	165	157	151	146	141	136	132	125	120	100	90	83	78	75	73	72
800	463	328	269	233	209	192	178	167	158	150	143	138	133	128	124	120	114	109	92	82	75	71	69	67	65
850	434	308	252	219	196	179	167	156	148	140	134	129	124	120	116	113	107	102	86	77	71	67	64	62	61
900	406	288	235	204	183	168	156	146	138	131	125	120	116	112	109	105	100	95	80	72	66	62	60	58	57
950	378	268	219	190	171	156	145	136	129	122	117	112	108	105	101	98	93	89	75	67	62	58	56	54	53
1000	351	249	204	177	159	145	135	126	120	114	109	104	101	97	94	91	87	83	69	62	57	54	52	51	50
1050	325	231	189	164	147	134	125	117	111	105	101	97	93	90	87	85	80	76	64	57	53	50	48	47	46
1100	282	200	164	142	128	117	108	102	96	91	87	84	81	78	76	73	70	66	56	50	46	43	42	41	40
1150	257	182	149	129	116	106	98	92	87	83	79	76	73	71	69	67	63	60	51	45	42	39	38	37	36
1200	211	149	122	106	95	87	81	76	72	68	65	63	60	58	56	55	52	50	42	37	34	32	31	30	30
1250	183	130	106	92	83	76	70	66	62	59	57	54	52	51	49	48	45	43	36	32	30	28	27	26	26
1300	154	109	89	78	70	64	59	55	52	50	48	46	44	43	41	40	38	36	30	27	25	24	23	22	22

Table 3

GUIDELINES FOR LEFT-TURN LANE AT UNSIGNALIZED INTERSECTION

Four-lane Roadway Undivided

Opposing Volume (vph)												Advancing Volume - vph													
Left-turn - percent												Opposing Volume (vph)													
1.0	2.5	5.0	10	15	20	30	40	50	1.0	2.5	5.0	10	15	20	30	40	50	1.0	2.5	5.0	10	15	20	30	
50	1615	1030	737	536	450	402	351	328	321	1430	912	653	475	399	356	311	291	285	276	191	139	101	73	52	37
100	1431	912	653	475	399	356	311	291	285	1271	810	580	421	354	316	276	258	253	242	177	127	96	71	51	33
150	1271	810	580	421	354	316	276	258	253	1140	727	521	378	318	284	248	232	227	215	177	127	96	71	51	33
200	1140	727	521	378	318	284	248	232	227	1028	655	469	341	287	256	223	209	205	200	164	147	134	125	117	111
250	1028	655	469	341	287	256	223	209	205	914	582	417	303	255	227	198	186	182	176	144	137	130	124	117	111
300	914	582	417	303	255	227	198	186	182	824	525	376	273	230	205	179	167	164	159	137	130	124	117	111	106
350	824	525	376	273	230	205	179	167	164	739	471	338	245	206	184	161	150	147	142	128	117	108	102	96	91
400	739	471	338	245	206	184	161	150	147	658	419	300	218	183	164	143	134	131	128	116	106	98	92	87	83
450	658	419	300	218	183	164	143	134	131	590	376	269	196	164	147	128	120	117	111	106	94	88	83	77	76
500	590	376	269	196	164	147	128	120	117	529	337	242	176	147	132	115	107	105	100	91	85	80	75	70	66
550	529	337	242	176	147	132	115	107	105	470	300	215	156	131	117	102	96	94	88	79	73	67	63	58	51
600	470	300	215	156	131	117	102	96	94	419	267	191	139	117	104	91	85	83	77	71	66	60	51	45	42
650	419	267	191	139	117	104	91	85	83	379	242	173	126	106	94	82	77	76	70	66	60	51	45	42	37
700	379	242	173	126	106	94	82	77	76	342	218	156	113	95	85	74	69	68	63	58	56	52	50	47	43
750	342	218	156	113	95	85	74	69	68	308	196	140	102	86	77	67	62	61	58	56	52	50	47	43	40
800	308	196	140	102	86	77	67	62	61	276	176	126	91	77	69	60	56	55	52	50	47	43	40	37	33
850	2																								

Table 4

GUIDELINES FOR LEFT-TURN LANE AT UNSIGNALIZED INTERSECTION

Four-lane Roadway		Divided							
Opposing Volume (vph)	Advancing Volume - vph								
	Left-turn - percent								
	1.0	2.5	5.0	10	15	20	30	40	50
50	2480	1580	1132	822	691	617	538	504	493
100	2197	1400	1003	729	612	546	477	446	437
150	1950	1243	890	647	544	485	423	396	388
200	1750	1115	799	581	488	435	380	355	348
250	1578	1006	721	524	440	393	343	321	314
300	1403	894	640	465	391	349	305	285	279
350	1265	806	578	420	353	315	275	257	252
400	1135	723	518	376	316	282	246	231	226
450	1010	644	461	335	282	251	219	205	201
500	906	577	413	300	252	225	197	184	180
550	813	518	371	269	226	202	176	165	162
600	722	460	330	240	201	180	157	147	144
650	643	410	293	213	179	160	140	131	128
700	583	371	266	193	162	145	126	118	116
750	524	334	239	174	146	130	114	107	104
800	472	301	216	157	132	117	103	96	94
850	423	270	193	140	118	105	92	86	84
900	376	240	172	125	105	93	82	76	75
950	331	211	151	110	92	82	72	67	66
1000	299	191	137	99	83	74	65	61	60
1100	230	147	105	76	64	57	50	47	46
1200	175	112	80	58	49	44	38	36	35
1300	140	89	64	46	39	35	30	28	28
1400	113	72	52	38	32	28	25	23	23
1500	92	59	42	31	26	23	20	19	18
1600	75	48	34	25	21	19	16	15	15
1700	62	40	28	21	17	16	14	13	12
1800	48	30	22	16	13	12	10	10	9

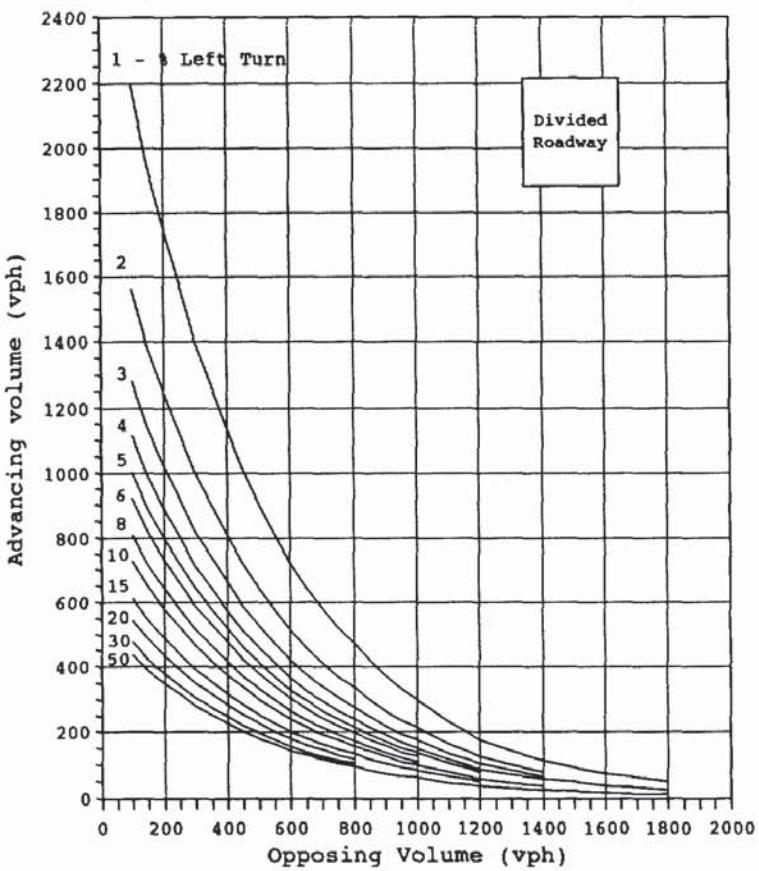


Figure 4 Guidelines for Left-turn Lane at Unsignalized Intersection - Four-lane, Divided Roadway

Table 5

Opposing Volume (vph)	Green Time/Cycle Length Ratio (G/C)																										
	0.10			0.20			0.30			0.40			0.50			0.60			0.70			0.80			0.90		
	50	85	95	50	85	95	50	85	95	50	85	95	50	85	95	50	85	95	50	85	95	50	85	95	50	85	95
50	75	25	25	125	50	25	175	75	25	225	100	50	275	125	50	325	125	50	375	150	75	425	175	75	475	200	75
100	75	25	25	125	50	25	175	75	25	225	100	50	275	100	50	325	125	50	375	150	75	425	175	75	475	200	75
150	50	25	25	100	50	25	150	75	25	200	100	50	250	100	50	300	125	50	350	150	75	400	175	75	450	175	75
200	50	25	25	100	50	25	150	75	25	200	75	50	250	100	50	300	125	50	325	150	50	375	150	75	425	175	75
250	50	25	25	100	50	25	150	75	25	200	75	50	225	100	50	275	125	50	325	125	50	375	150	75	400	175	75
300	50	25	25	100	50	25	150	50	25	175	75	50	225	100	50	275	100	50	300	125	50	350	150	75	400	150	75
350	50	25	25	100	50	25	125	50	25	175	75	25	225	100	50	250	100	50	300	125	50	325	150	50	375	150	75
400	50	25	25	100	50	25	125	50	25	175	75	25	200	100	50	250	100	50	275	125	50	325	125	50	350	150	75
450	50	25	25	75	50	25	125	50	25	150	75	25	200	75	50	225	100	50	275	125	50	300	125	50	350	150	50
500	50	25	25	75	50	25	125	50	25	150	75	25	175	75	50	225	100	50	250	100	50	300	125	50	325	125	50
550	50	25	25	75	50	25	100	50	25	150	75	25	175	75	25	200	100	50	250	100	50	275	125	50	300	125	50
600	25	25	25	75	25	25	100	50	25	125	50	25	175	75	25	200	75	50	225	100	50	250	100	50	300	125	50
650	25	25	25	75	25	25	100	50	25	125	50	25	150	75	25	175	75	50	225	100	50	250	100	50	275	125	50
700	25	25	25	75	25	25	100	50	25	125	50	25	150	75	25	175	75	25	200	75	50	225	100	50	250	100	50
750	25	25	25	75	25	25	100	50	25	125	50	25	150	50	25	175	75	25	200	75	50	225	100	50	250	100	50
800	25	25	25	50	25	25	75	50	25	100	50	25	125	50	25	150	75	25	175	75	25	200	75	50	225	100	50
850	25	25	25	50	25	25	75	25	25	100	50	25	125	50	25	150	50	25	150	75	25	175	75	50	200	75	50
900	25	25	25	50	25	25	75	25	25	100	50	25	100	50	25	125	50	25	150	75	25	175	75	25	175	75	50
950	25	25	25	50	25	25	75	25	25	75	50	25	100	50	25	125	50	25	125	50	25	150	75	25	175	75	25
1000	25	25	25	25	25	25	50	25	25	75	25	25	100	50	25	100	50	25	100	50	25	125	50	25	125	50	25

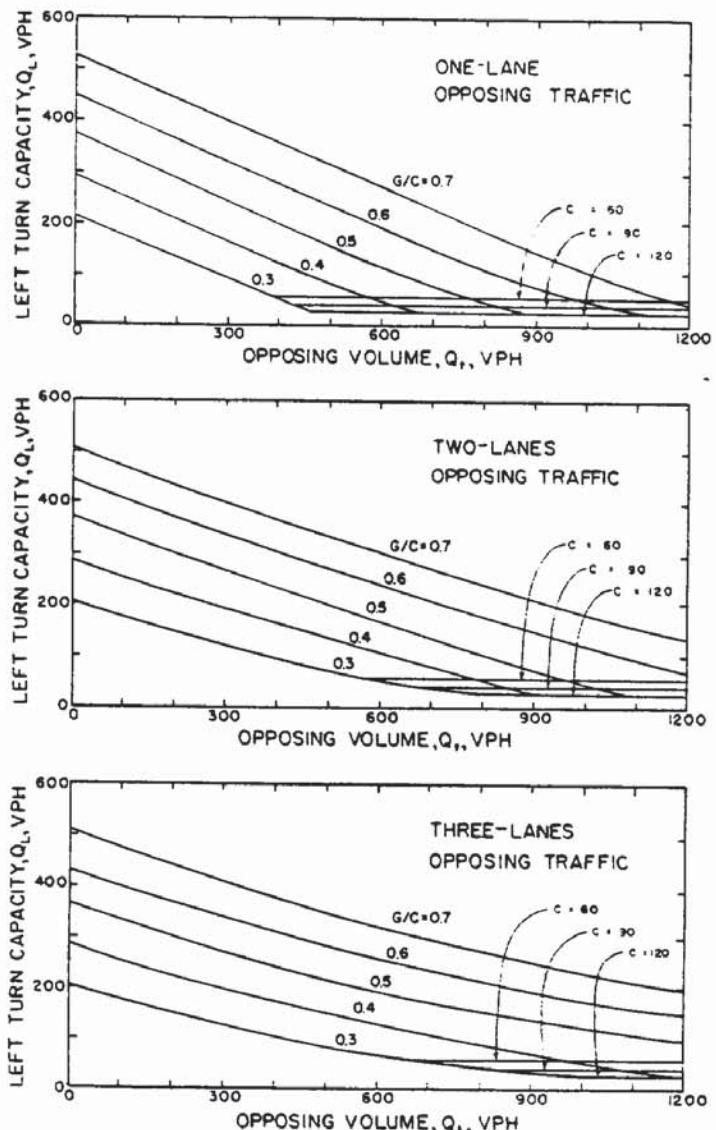


Figure 5 Left-turn Capacity for Approaches with a Two-phase Signal and No Left-turn Lane - Uncorrected for Trucks and Buses

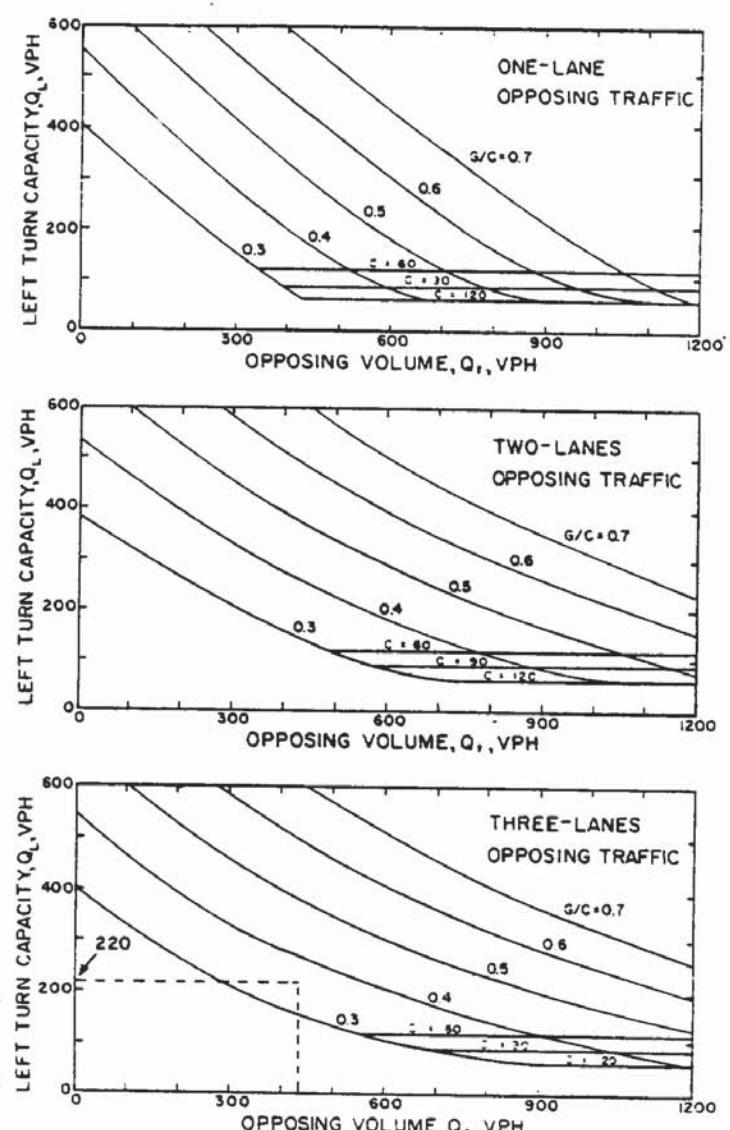


Figure 6 Left-turn Capacity for Approaches with a Two-phase Signal and a Left-turn Lane - Uncorrected for Trucks and Buses

COMMITTEE PERSONNEL

Joseph C. Oppenlander, Chairperson
 Shyamal Basu
 W. Martin Bretherton, Jr.
 Jay H. Calhoun
 Milton Carrasco
 Olin K. Dart
 Michael F. Hankey

John W. Herzke
 Frank J. Koepke
 Fernando M. Montenegro
 Stephen G. Pernaw
 Michael C. Pietrzyk
 Seyed Safavian
 Greg T. Smith
 Nick A. Theophilopoulos
 J. Christopher Bianchi, Student Researcher